Effects of Hydride Re-orientation and Hydride Rim on Fracture Energy of Zircaloy-4 Cladding

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1. Introduction

Spent nuclear fuel (SNF) is subjected to a vacuum drying process at up to 400 ℃ and cooled down during dry storage. In this process, hydrides are re-precipitated in the zirconium matrix and these re-precipitated hydrides reduce the ductility of the fuel claddings. Then the claddings can be easily damaged by external impacts such as pinch-type loading that can happen during SNF transportation. Many studies have been carried out on the integrity degradation of the claddings, but most of which have uniform hydride morphology. Some phenomena, such as hydride rim and hydride re-orientation, can occur in SNF claddings and they can worse the integrity of the claddings more than uniformly precipitated hydrides. In this study, hydrogen charging and hydride re-orientation treatment were implemented to simulate SNF claddings and ring compression tests were adopted as a test method to evaluate the fracture energy of claddings which shall be subjected to shock loads during transportation. Then, effects of hydride re-orientation and hydride rim on fracture energy were analyzed based on the RCT results.

2. Experimental

2.1 Specimen preparation

In this work, cold worked stress relieved (CWSR) Zircaloy-4 cladding tube with outer diameter of 9.5 mm and wall thickness of 0.57 mm was used. Two types of specimens were prepared to evaluate an effect of hydride rim: uniform hydride specimens (U1-U4) and hydride rim specimens (R1-R4). To form hydride rim, outer surface of cladding tube was plated with Ni, which has good hydrogen affinity before hydrogen charging [1]. Then, specimens were charged with hydrogen using a Sievert type apparatus. After hydrogen charging, to form hydride re-orientation specimens were pressurized by argon gas at initial hoop stresses of 90-150 MPa at 400 ℃. Hydrogen contents of the specimen were determined using a hydrogen analyzer (ELTRA ONH-2000).

Table 1. Conditions of specimen used in this study

	specimen	Hydrogen concentration (wppm)	Initial hoop stress at 400℃ (MPa)	Peak Temperature (℃)
Uniform hydride specimen	U1	272	150	400
	U2	272	140	
	U3	262	110	
	U4	191	90	
Hydride rim specimen	R1	1246	150	400
	R2	1281	140	
	R3	1148	110	
	R4	931	90	

2.2 Ring compression test

Ring compression test (RCT) was conducted at a temperature range of room temperature (RT) to 300℃ using a universal testing machine (INSTRON model 5582) with a displacement rate of 1 mm/min.

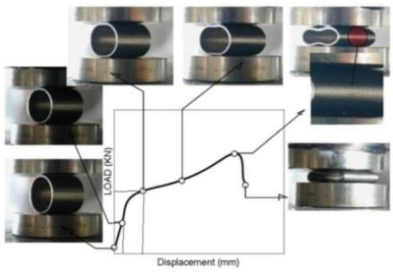


Fig. 1. Ring compression test and load-displacement curve.

3. Results and discussions

Based on the RCT results, fracture energy of SNF claddings was evaluated on two parameters: (1) degree of hydride re-orientation, and (2) ductile to brittle transition temperature (DBTT).

3.1 Fracture energy/area by degree of hydride re-orientation

In RCT, cladding ductility can be evaluated by fracture energy/area similar to strain energy density (SED) concept [2]. Radial hydride continuity factor (RHCF) is one of methods that indicate degree of hydride re-orientation [3]. Fig. 3 shows fracture energy/area by RHCF with hydride rim specimens

(R1-R3 and U1-U3) at a temperature ranges from RT to 150℃. The fracture energy/area at RT, 100℃ and 150℃ decreases with an increase in the RHCF. It means that radial hydride can be an important factor to evaluate facture energy of claddings.

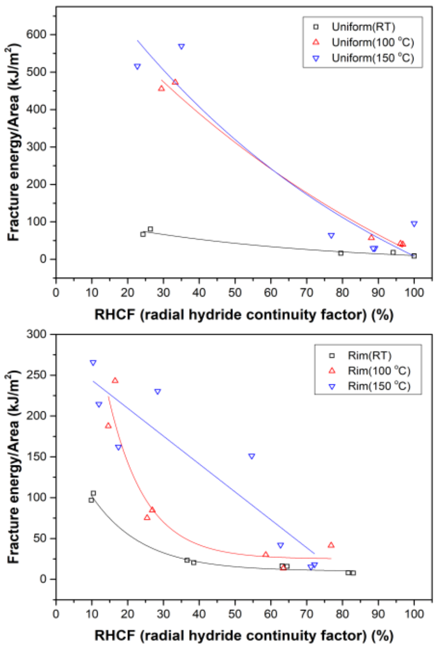
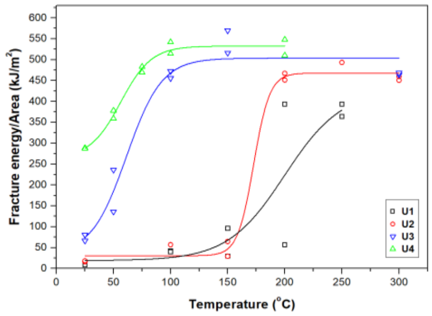


Fig. 2. Fracture energy/area by radial hydride continuity factor.

3.2 Ductile to brittle transition temperature (DBTT)

Ductile to brittle transition temperature (DBTT) is important as claddings slowly cooled down after vacuum drying process. If claddings become brittle as temperature goes down, cladding rupture can happen by external impact during transportation. Fig. 3 is fracture energy/area by the temperature of uniform hydride specimens (U1-U4) and hydride rim specimens (R1-R4). DBTT of claddings increases as cladding hoop stress increases. It is considered that radial hydrides can be more easily generated as hoop stress goes up and they make claddings brittle. With high hoop stress (e.g. U1, U2, R1, and R2), claddings can be brittle even in 150-200℃. Claddings with hydride rim can be ruptured by low external energy although cladding hoop stress is low.



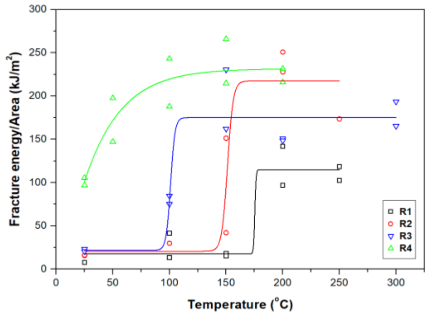


Fig. 3. Fracture energy/area by the temperature of uniform hydride (U1-U4) and hydride rim specimens (R1-R4).

4. Conclusions

RCTs were conducted using uniform hydride specimens and hydride rim specimens treated hydride re-orientation in 90-150 MPa at a temperature ranges from RT to 200℃. Mechanical properties of SNF claddings were evaluated on two parameters, and results are as follows:

(1) The fracture energy/area at RT, 100℃ and 150℃ decreases with an increase in the RHCF. Radial hydride can be an important factor to evaluate facture energy of claddings.

(2) With high hoop stress (e.g. U1, U2, R1, and R2), claddings can be brittle even in 150-200℃. Claddings with hydride rim can be ruptured by low external energy although cladding hoop stress is low.

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